TELEOPERATORS

Dr. Antal K. Bejczy
Senior Research Scientist
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

1. INTRODUCTION

Historically, teleoperator systems were developed in the U.S.A. in the mid-forties of the 20th century to create capabilities for handling highly radioactive material. Teleoperators allowed a human operator to handle radioactive material from a workroom separated by a one meter thick radiation absorbing concrete wall from the radioactive environment. The operator could observe the task scene through radiation resistant viewing ports in the wall. The development of teleoperators for the nuclear industry culminated in the introduction of bilateral force-reflecting master-slave manipulator systems. In these very successful systems, the slave arm at the remote site is mechanically or electrically coupled to the geometrically identical or similar master arm handled by the operator, and follows the motion of the master arm. The coupling between the master and slave arms is a two-way coupling: inertia or work forces exerted on the slave arm can back-drive the master arm, enabling the operator to feel the forces that are acting on the slave arm. Force information available to the operator is an essential requirement for dexterous control of remote manipulators, since general-purpose manipulation consists of a series of well-controlled contacts between handling device and objects and also implies the transfer of forces and torques from the handling device to objects.

In a general sense, teleoperator devices enable human operators to remotely perform mechanical actions that usually are performed by the human arm and hand. Thus, teleoperators, or the act of teleoperation, extends the manipulative capabilities of the human arm and hand to remote, physically hostile or dangerous environments. In this sense, teleoperation conquers space barriers in performing manipulative mechanical actions at remote sites, like telecommunication conquers space barriers in transmitting information to distant places.

in a more modern point of view, teleoperators are specialized robots, called telerobots, performing manipulative mechanical work remotely there where humans can not go or do not want to go. Following this viewpoint, current practice in advanced robotics is divided into two main areas: industrial robotics and telerobotics or robotic teleoperation. Industrial robots arc used as an integral part of manufacturing processes and within the frame of production engineering techniques to perform repetitive work in a structured factory environment. The characteristic control of industrial robots is a programmable sequence controller that functions autonomous] y with only occasional human intervention, either to reprogram or retool for a new task or to correct for an interruption in the work flow. Teleoperator robots, on the other hand, serve to extend, through mechanical, sensing and computational techniques, the human manipulative, perceptive and cognitive abilities into an environment that is either hostile to or remote from the human operator. Teleoperator robots or, in today's terminology, telerobots typically perform non-repetitive or singular, servicing, maintenance or repair work under a variety of environmental conditions ranging from structured to unstructured conditions. Telerobot control is characterized by a direct involvement of the human operator in the control since, by definition of task requirements, teleoperator systems extend human manipulative, perceptual and cognitive skills to remote places.

Continuous human operator control in teleoperation has both advantages and disadvantages. The main advantage is that overall task control can rely on human perception, judgement, decision, dexterity and training. The main disadvantage is that the human operator must cope with a sense of remoteness, be alert of and integrate many information and control variables, and coordinate the control of one or two mechanical arms each having many (typically six) degrees of freedom - and doing all these with limited human resources. Furthermore, in many cases like space and deep sea applications, communication time delay interferes with continuous human operator control.

Modern development trends in teleoperator control technology are aimed at amplifying the advantages and alleviating the disadvantages of the human element in teleoperator control by the development and use of advanced sensing and graphics displays, intelligent computer controls, and new computer-based human-machine interface devices and techniques in the information and control channels. The use of model and sensor data driven automation in teleoperation offers significant new possibilities to enhance overall task performance by providing efficient means for task-level controls and displays.

Automation in teleoperation is distinguished from other forms of automated systems by the explicit and active inclusion of the human operator in system control and information management. Such active participation by the human, interacting with automated system elements in teleoperation is characterized by several levels of control and communication, and can be conceptualized under the notion of "supervisory control" as discussed in [1]. The human-machine interaction levels in teleoperation can be considered in a hierarchic arrangement: (i) planning or high level algorithmic functions, (ii) motor or actuator control functions, and (iii) environmental interaction sensing functions. These functions take place in a task context in which the level of system automation is determined by (a) the mechanical and sensing capabilities of the telerobot system, (b) real time constraints on computational capabilities to deal with control, communication and sensing, (c) the amount, format, content and mode of operator interaction with the telerobot system, (d) environmental constraints, like task complexity and (e) overall system constraints, like operator's skill or maturity of machine intelligence techniques.

Some advances have been made in teleoperator technology through the introduction of various sensors, computers, automation and new human-machine interface devices and techniques for remote manipulator control. The development of advanced teleoperator technology is a challenging multidisciplinary effort. But, like the creation of a new tool, it is not a simple sum of other technologies. It represents a field of applied science and engineering on its own right, and requires its own experimental base.

The subsequent part of this chapter is focused on the description and some practical evaluation of an experimental Advanced Teleoperation (ATOP) system as an illustrative example of this evolving technology. This ATOP system was developed at the Jet Propulsion Laboratory (JPL) in the nineteen-eighties through 1993.

II. ADVANCED TELEOPERATION

The JPL ATOP system setting was conceived to provide a dual arm robot system together with the necessary operator interfaces to extend the two-handed manipulation capabilities of a human operator to remote places. The system setting intends to include all perceptive components that are necessary to perform sensitive remote manipulation efficiently, including nonrepetitive and unexpected tasks. The overall system is divided into two major parts: the remote robot work site and the local control station site, with electronic data and TV communication links between the two sites.

Remote Work Site

The remote site is a workcell. It comprises: 1) two redundant eight-DOF arms (produced by AAl Company, Inc.) in a fixed base setting, each covering a hemispheric work volume, and each equipped with the latest JPL-developed model C smart hands that contain three-dimensional force-moment sensors at the hands' base and grasp force sensing at the base of the hand claws; 2) a JPL-developed control electronics and distributed computing system for the two arms and smart hands; and 3) a computer controllable multi-TV gantry robot system with controllable illumination. This gantry robot accommodates three color TV cameras, one on the ceiling plane, one on the rear plane, and one on the right side plane of the workcell. Each camera can be position controlled in two translational DOF in the respective plane, and in two orientation directions (pan and tilt) relative to the respective moving base. Zoom, focus, and iris of each TV camera can also be computer controlled. A stereo TV camera system is also available which can be mounted on any of the two side camera bases. The total size of the rectangular remote work site is about 5 m in width, about 4 m in depth, and about 2.5 m in height. See Fig. 1 for the ATOP remote workcell.

Control Station

The control station site organization follows the idea of accommodating the human operator in all levels of human-machine interaction, and in all forms of human machine interfaces. Presently, it comprises 1) two general purpose force-reflecting hand controllers (FRHC), 2) three

TV monitors, 3) TV camera/monitor switchboards, 4) a manual input device for TV control, and 5) three graphics displays. One of these graphics displays is connected to the primary graphics workstation (IRIS 4D/310 VGX) which is used for preview/predictive displays and for various graphical user interfaces (GUIs) in four-quadrant format. The second is connected to an IRIS 4D/70 GT workstation and is solely used for sensor data display. The third one is connected to a SUN workstation (SparcStation 10) and is used as a control configuration editor (CCE), which is an operator interface to the manipulators' control software based on an X-window environment. See Fig. 2 for the ATOP local control station.

Hand Controllers

The human arm-hand system (thereafter simply called hand) is a key communication medium in teleoperator control. With hand actions, complex position, rate, or force commands can be formulated and very physically written to the controller of a remote robot arm system in all workspace directions. At the same time, the human hand also can receive force, torque, and touch information from the remote robot arm-hand system. Furthermore, the human fingers offer additional capabilities to convey new commands to a remote robot controller from a suitable hand controller. Hand controller technology is, therefore, an important technology in the development of advanced teleoperation. Its importance is particularly underlined when one considers computer control which connects the hand controller to the remote arm system. The direct and continuous (scaled or unscaled) relation of operator hand motion to the remote robot arm's motion behavior in real time through a hand controller is in sharp contrast to the computer keyboard type commands which, by their very nature, are symbolic, abstract, and discrete (noncontinuous), and require the specification of some set of parameters within the context of a desired motion.

in contrast to the standard force-reflecting, replica master-slave systems, a new form of bilateral, force-reflecting manual control of robot arms has been implemented at the JPL ATOP project. The hand controller is a backdrivable six-DOF isotonic joystick. It is dissimilar to the controlled robot arm both cinematically and dynamically. But, thı ough computer transformations, it can control the motion of any robot arm in six task space coordinates (in three position and three orientation coordinates). Forces and moments sensed at the base of the robot hand can backdrive the hand controller through proper computer transformati ons so that the operator feels the forces and moments acting at the robot hand while he controls the position ancl orientation of it. This hand controller can read the position and orientation of the hand grip within a 30-cm cube in all orientations, and can apply arbitrary force and moment vectors up to 20 N and 1.0 Nm, respectively, at the hand grip (Two FRHC's arc visible in Fig. 2.) More details of the mechanical design of this hand controller and on hand controller technology in general can be found in [2 and 3]. A computer-based control system establishes the appropriate kinematic and dynamic control relations between the FRHC and the robot arm. The FRHC can control any robot arm and can receive force/torque feedback from any robot arm equipped with a three-dimensional force-moment sensor at the base of the robot hand.

The computer-based control system supports four modes of manual control: position, rate, force-reflecting, and compliant control in task space (Cartesian space) coordinates. The operator, through an on-screen menu, can designate the control mode for each task space axis independently. The *position control mode servos the* slave position and orientation to match the master's. The *indexing function* allows slave excursions larger or smaller than the 30-cm cube hand controller work volume. In the *force-reflecting mode*, the hand controller is backdriven based on force-moment data generated by the robot and sensed during the robot hand's interaction with objects and environment. The *rate control mode* sets the slave endpoint velocity in task space based on the displacement of the hand controller. This is implemented through a software spring in the control computer of the hand controller. Through this software spring, the operator has a sensation of the commanded rate, and the software spring also provides a zero-refcrenced restoring force. The rate mode is useful for tasks requiring large translations. The *compliant control mode is* implemented through a low-pass software filter acting on the robot hand's force-torque sensor data in the hybrid position-force loop. This permits the operator to control a springy or less stiff robot. Active compliance with damping can be varied by changing the filter parameters in the software menu. Setting the spring, parameter to zero in the low-pass filter will reduce it to a pure damper which results in a high stiffness hybrid position-force control loop.

Control System

The overall ATOP control organization permits a spectrum of operations between full manual, shared manual and automatic, and full automatic (call traded) control, and the control can be operated with variable active compliance referenced to force-moment sensor data. More on the overall ATOP control system can be found in [4-9]. The overall control/information data flow diagram (for a single arm) is shown in Fig. 3. It is noted that the computing architecture of this original ATOP system is a fully synchronized pipeline, where the local servo loops at both the control station and the remote manipulator nodes can operate at a 1000-Hz rate. The end-to-end bilateral (i.e., force-reflecting) control loop can operate at a 200-Hz rate.

The data flow diagram shown in Fig. 3 illustrates the organization of several servo loops in the system. The innermost loop is the position control servo at the robot site. This servo uses a PD control algorithm, where the damping is purely a function of the robot joint velocities. The incoming data to this servo is the desired robot trajectory described as a sequence of points at 1 ms intervals. This joint servo is augmented by a gravity compensate on routine to prevent the weight of the robot from causing a joint positioning error. Because this servo is a first-order servo, there will be a constant position error that is proportional to the joint velocity.

in the basic Cartesian control mode the data from the hand controller are added to the previous desired Cartesian position. Form this the inverse kinematics generate the desired joint positions. The joint servo moves the robot to this position. From the actual joint position the forward kinematics compute the actual Cartesian positions. The force-torque sensor data and the actual positions are fed back to the hand controller side to provide force feedback.

This basic mode can be augmented by the addition of compliance control, Cartesian servo, and sticktion/friction compensation. Figure 4 shows the compliance control and the Cartesian servo augmentations. There are two forms of compliance, an integrating and a spring type (see Fig. 5). In integrating compliance the velocity of the robot end effecter is proportional to the force felt in the corresponding direction. To eliminate drift a deadband is used. The zero velocity band does not have to be a zero force, a force offset may be used. Such a force offset is used if, for example, wc want to push against the task board at some given force while moving along other axes. Any form of compliance can be selected along any axis independently. In the case of the spring-t ypc compliance the robot position is proportional to the sensed force. This is similar to a spring centering action. The velocity of the robot motion is limited in both the integrating and spring cases.

There is a wide discrepancy between the robot response bandwidth and the force readings. The forces are read at a 1000-Hz sampling rate. The robot motion command has an output response at a 5-Hz bandwidth. To generate smooth compliance response, the force readings go through two subsequent filters. The first one is a simple averaging of ten force readings. This average is called 100-Hz force and is computed at a 100-1 Iz rate. From this 100-Hz force a 5-Hz force reading is computed by a first-order low-pass filter. This 5-Hz force reading is also computed at a 100-Hz rate. The 5-Hz force is used for compliance computations.

As shown in Fig. 4, the Cartesian servo acts on task space (X, Y, Z, pitch, yaw, roll) errors directly. These errors are the difference between desired and actual task space values. The actual task space values are computed from the forward kinematic transformation of the actual joint positions. This error is then added to the new desired task space values before the inverse kinematic transformation determines the new joint position commands from the new task space commands.

A trajectory generator algorithm was formulated based on observations of profiles of task space trajectories generated by the operators manually through the FRHC. Three important features were observed in hand-generated task space trajectory profiles:

1) The operators always generated trajectories as a function of the relative distance between start point and goal point in the task space or, in general, as a function of the present position state relative to the desired position state of the end effecter in the task space. in other words, the operators did not manually generate trajectories based on time (on clock signals).

2) The velocity-position phase diagrams of motion typically resembled a harmonic (sine) function.

3) Between the start and completion phases, the operator-generated trajectories typically attained a constant velocity profile.

Based on these observations, wc formulated a harmonic motion generator (HMG) with a sinusoidal velocity-posilion phase function profile as shown in Fig. 6. The motion is parameterized by the total distance traveled, the maximum velocity, and the distance used for acceleration and deceleration. Both the accelerating, and decelerating segments are quarter sine waves, with a constant velocity segment connecting them. This scheme still has a problem, the velocity being O before the motion starts. This problem is corrected by adding a small constant to the velocity function.

It is noted that the HMG discussed here is quite different from the typical trajectory generator algorithms employed in robotics which use a polynomial position-time function. Our algorithm generates the motion as a trigonometric (harmonic) velocity vs position function. The position vs time and the corresponding velocity vs time functions generated by the HMG are shown in Fig. 7. More on performance results generated by HMG, Cartesian servo, and force-torque sensor data filtering in compliance control can be found in [5 and 9]. Illustrative examples are shown in Fig. 8 and Fig. 9.

Computer Graphics

Task visualization is a key problem in teleoperation, because most of the operator's control decisions are based on visual or visually conveyed information, For this reason, computer graphics play an increasingly important role in advanced teleoperation. This role includes 1) planning actions, 2) previewing motions, 3) predicting motions in real time under communication time delay, 4) helping operator training, 5) enabling visual perception of nonvisible events like forces and moments, and 6) serving as a flexible operator interface to the computerized control system.

The actual utility of computer graphics in teleoperation depends to a high degree on the fidelity of graphics models that represent the teleoperated system, the task, and the task environment. In the past few years the JPL ATOP project developed high-fidelity calibration of graphics images to actual TV images of task scenes. This development has four major ingredients: first, the creation of high-fidelity three-dimensional graphics models of robot arms and objects of interest for robot arm tasks; second, the high-fidelity calibration of the three-dimensional graphics models relative to given TV camera two-dimensional image frames which cover the sight of both the robot arm and the objects of interest; third, the high-fidelity overlay of the calibrated graphics models over the actual robot arm and object images in a given TV camera image frame on a monitor screen; fourth, the high-fidelity motion control of robot arm graphics image by using the same control soft ware that drives the real robot.

The high-fidelity fused virtual and actual reality image displays became very useful tools for planning, previewing, and predicting robot arm motions without commanding and moving the robot hardware. The operator can generate visual effects of robot motion by commanding and controlling the motion of the robot's graphics image superimposed over TV pictures of the live scene. Thus, the operator can see the consequences of motion commands in real time, before sending the commands to the remotely located robot. The calibrated virtual reality display system can also provide high-fidelity synthetic or artificial TV camera views to the operator. These synthetic views can make critical motion events visible that are otherwise hidden from the operator in a given TV camera view or for which no TV camera view is available. More on the graphics system in the ATOP control station can be found in [10-14].

High-Fidelity Graphics Calibration

A high-fidelity overlay of graphics and TV images of work scenes requires a high-fidelity TV camera calibration and object localization relative to the displayed TV camera view. Theoretically, this can be accomplished in several ways. For the purpose of simplicity and operator-controllable reliability, an operator-interactive camera calibration and object localization technique has been developed, using the robot arm itself as a calibration fixture, and using a nonlinear least-squares algorithm combined with a linear algorithm as a new approach to compute accurate calibration and localization parameters.

The current method uses a point-to-point mapping procedure, and the computation of camera parameters is based on the ideal pinhole model of image formation by the camera. In the camera calibration procedure, the operator first enters the correspondence information between the three-dimensional graphics model points and the two-dimensional camera image points of the robot arm to the computer, This is performed by repeatedly clicking with a mouse a graphics model point and its corresponding TV image point for each corresponding pair of points on a monitor screen which, in a four-quadrant window arrangement, shows both the graphics model and the actual TV camera image (see Fig. 10). To improve calibration accuracy, several poses of the manipulator within the same TV camera view can be used to enter corresponding graphics model and TV image points to the computer. Then the computer computes the camera calibration parameters, Because of the ideal pinhole model assumption, the computed output is a single linear 4 x 3 calibration matrix for a linear perspective projection.

Object localization is performed after camera calibration by entering corresponding object model and TV image points to the computer for different TV camera views of the object. Again, the computational output is a single linear 4 x 3 calibration matrix for a linear perspective projection.

The actual camera calibration and object localization computations are carried out by a combination of linear and nonlinear least-squares algorithms. The linear algorithm, in general, does not guarantee the orthonormality of the rotation matrix, providing only an approximate solution. The nonlinear algorithm provides the least-squares solution that satisfies the orthonormality of the rotation matrix, but requires a good initial guess for a convergent solution without entering into a very time-consuming random search. When a reasonable approximate solution is known, one can start with the nonlinear algorithm directly. When an approximate solution is not known, the linear algorithm can be used to find one, and then one can proceed with the nonlinear algorithm. More on the calibration and object localization technique can be found in [15, 16].

After completion of camera calibration and object localization, the graphics models of both the robot arm and the object of interest can be overlaid with high fidelity on the corresponding actual images of a given TV camera view. The overlays can be in wire-frame or solid-shaded polygonal rendering with varying levels of transparency, providing different task details. In the wire-frame format, the hidden lines can be removed or retained by the operator, depending on the information needs in a given task.

Graphics operator interface

The first graphic system as an advanced operator interface was aimed at parameter acquisition, an was handled as a teleoperation configuration editor (TCE) described in [17]. This interface used the concepts of windows, icons, menus, and a pointing device to allow the operator to interact, select, and update single parameters as well as a group of parameters. TCE utilizes the direct manipulation concept, with the central idea of having visible objects such as buttons, sliders, and icons that can be manipulated directly, i.e., moved and selected using the mouse, to perform any operation. A graphic interface of this type has several advantages over a traditional panel of physical buttons, switches, and knobs: the layout can be easily modified and its implementation cycle, i.e., design and validation, is significant y shorter than hardware changes.

The TCE, Fig. 11, was developed to incorporate all the configuration parameters of an early single-arm version of the ATOP system. It was organized in a single menu divided into several areas dedicated to the parameters of a specific function. Dependencies among different graphical objects are embedded in the interface so that, when an object is activated, the TCE checks for parameter congruency. A significant feature of this implementation is its capability to store and retrieve sets of parameters via macro buttons. When a macro command is invoked, it saves the current system configuration and stores it in a function button which can later restore it. The peg-in-hole task, for instance, requires mostly translational motions but when holes have a tight clearance, a compliance is necessary. An appropriate macro configuration is one that enables x, y, and z axes, with position control in the approach direction and automatic compliance on the other two axes. This configuration can be assigned to a macro button and then recalled during a task containing a peg-in-hole segment.

The continuing work on a graphic system as an advanced operator interface was aimed at the data presentation structure of the interface problem, and, for that purpose, used a hierarchical architect ure [14]. This hierarchical data interface looks like a menu tree with only the last menu of the chain (the leaf) displaying data. All the ancestors of the leaf are visible to clearly indicate the nature of the data displayed, The content of the leaf includes data or pictures and quickly conveys the various choices available to the operator. A schematic figure of this layout is shown in Fig. 12. Parameters have been organized in four large groups that follow the sequence of steps in a teleoperation protocol. These groups are 1) layout, 2) configuration, 3) tools, and 4) execution. Each group is further subdivided into specific functions. The layout menu tree contains the parameters defining the physical task structure, such as the relative position of the robots and of the FRHC, servo rates, etc. The configuration menu tree contains the parameters necessary to define task phases, such as control mode and control gains. The tools tree contains parameters and commands for the off-line support to the operator, such as planning, redundancy resolution, and software development. Finally, the execution tree cent ai ns commands and parameters necessary while teleoperating the manipulators, such as data acquisition, monitoring of robots, hand controllers and smart hands, retrieval of stored configurations, and camera commands.

Generic Task Experiments

Generic tasks are idealized, simplified tasks and serve the purpose of evaluating some specific ATOP features. In these experiments, described in detail in [18], four tasks were used: attach and detach velcro, peg insertion and extraction, manipulation of three electrical connectors, and manipulation of a bayonet connector. Each task was broken down into subtasks. The test operators were chosen from a population with some technical background but not with an in-depth knowledge of robotics and teleoperation. Each test subject received 2-4 h of training on the control station equipment. The practice of individuals consisted of four to eight 30-min sessions.

As pointed out in [18], performance variation among the nine subjects was surprisingly slight. Their backgrounds were similar (engineering students or recent graduates) except for one who was a physical education major with training in gymnastics and coaching. This subject showed the best overall performance by each of the measures. This apparent correlation between performance and prior background might suggest that potential operators be grouped into classes based on interest and aptitudes.

The generic task experiments were focused at the evaluation of kinesthetic force feedback vs no force feedback, using the specific force feedback implementation techniques of the JPL ATOP project. The evaluation of the experimental data supports the idea that multiple measures of performance must bc used 10 characterize human performance in sensing and computer-aided teleoperation. For instance, in most cases kinesthetic force feedback significantly reduced task completion time. In some specific cases, however, it did not, but it did sharply reduce extraneous forces. More information on the results can be found in [18, 19].

Application Task Experiments

Application tasks in a laboratory setting simulate some real-world usc of ATOP. Two major application task experiments were performed: one without communication time delay and one with communication time delay.

The experiments without communication time delay were grouped around a simulated satellite repair task. The particular repair task was the duplication of the Solar Maximum Satellite Repair (SMSR) mission, which was performed by two astronauts in Earth orbit in the Space Shuttle Bay in 1983. Thus, it offered a realistic performance reference data base. This repair is a very challenging task, because this satellite was not designed for repair. Very specific auxiliary subtasks must bc performed (e.g., a hinge attachment) to accomplish the basic repair which, in our simulation, is the replacement of the main electric box (MEB) of the satellite. The total repair, as performed by two astronauts in Earth orbit, lasted for about 3 h, and comprised the following set of substasks: thermal blanket removal, hinge attachment for MEB opening, opening of the MEB, removal of electrical connectors, replacement of MEB, securing parts and cables, replug of electrical connectors, closing of MEB, and reinstating thermal blanket. It is noted that the two astronauts were trained for this repair on the ground for about a year, including many underwater trainings in a buoyancy tank.

The SMSR simulation by ATOP capabilities was organized so that each repair scenario had its own technical justification and performance evaluation objective. For instance, in the first subtask-scenario performance experiments, alternative control modes, alternative visual settings, operator skills vs training, and evaluation measures themselves were evaluated. See details in [20, 21]. The first subtask-scenario performance experiments involved thermal blanket cutting and reinstating, and unscrewing MEB bolts. That is, both subtasks implied the use of tools. Figure 13 illustrates these experiments.

Several important observations were made during the aforementioned subtask-scenario performance experiments. The two most important observations are that:

1) The remote control problem in any teleoperation mode and using any advanced component or technique is at least 50% a visual perception problem to the operator, influenced greatly by view angle, illumination, and contrasts in color or in shading.

2) The training or, more specifically, the training cycle has a dramatic effect upon operator performance. It was found that the first cycle should be regarded as a familiarization with the system and with the task. For a novice operator, this familiarization cycle should be repeated at least twice. The real training for performance evaluation can only start after completion of a familiarization cycle. The familiarization can be considered complete when the trainee understands the system 1/0 details, the system response to commands, and the task sequence details. During the second cycle of training, performance measurements should be made so that the operator understands the content of measures against which the performance will be evaluated, Note, that it is necessary to separate each cycle and repetitions within cycles by at least onc day. Once a personal skill has been formed by the operator as a consequence of the second training cycle, the real performance evaluation experiments can start. A useful criterion for determining the sufficient level of training can be, for instance, that of computing the ratio of standard deviation of completion time to mean completion time (that is computing the coefficient of variation). If the coefficient of variation of the last five trials of a subtask performance is less than 20%, then a sufficient level of training can be declared. In the subtask-scenario experiments quoted here, the real training, on the average, required one week per subject.

The practical purpose of training is, in essence, to help the operator develop a mental model of the system and of the task, During task execution, the operator acts through the aid of this mental model. It is, therefore, critical that the operator understands very well the response characteristics of the sensing and computer-aided ATOP system which has a variety of selectable control modes, adjustable control gains, and scale factors.

The procedure of operator training and the expected behavior of a skilled operator following an activity protocol offers the possibility of providing the operator with performance feedback messages on the operator interface graphics, derived from a stored model of the task execution.

A key element for such an advanced performance feedback tool to the operator is a program that can follow the evolution of a teleoperated task by segmenting the sensory data stream into appropriate phases,

A task segmentation program of this type has been implemented by means of a neural network architecture and it is able to identify the segments of a peg-in-hole task. See details in [22]. With this architecture, the temporal sequence of sensory data generated by the wrist sensor on the manipulators are turned into spatial patterns and a window of sensor observations which is related to the current task phase. A partially recurrent network algorithm was employed in the computation. Partially recurrent networks represent well the temporal evolution of a task, as they include in the input layer a set of nodes connected to the output units to create a context memory. These units represent the task phase already executed -- the previous state. Several experiments of the peg-in-hole task have been carried out and the results have been encouraging, with a percentage of correct segmentations approximately equal to 65%. More on these experiments can be found in [22, 23].

The experiments with communication time delay, conducted on a large laboratory scale in early 1993, utilized a simulated life-size satellite servicing task which was set up at the Goddard Space Flight Center (GSFC) and controlled 4000 km away from the JPL ATOP control station. Three fixed TV camera settings were used at the GSFC worksite, and TV images were sent to the JPL control station over the NASA-Select Satellite TV channel at video rate. Command and control data from JPL to GSFC and status and sensor data from GSFC to JPL were sent through the Internet computer communication network. The roundtrip command/information time delay varied between 4-8 s between the GSFC worksite an the JPL control station, dependent on the data communication protocol,

The task involved the exchange of a satellite module. This required inserting a 45-cm-long power screwdriver, attached to the robot arm, through a 45-cm-long hole to reach the module's latching mechanism at the module's backplane, unlatching the module from the satellite, connecting the module rigidly to the robot arm, and removing the module from the satellite. The placement of a new module back to the satellite's fame followed the reverse sequence of actions.

Four camera views were calibrated for this experiment, entering 15-20 correspondence points in total from three 10 four arm poses for each view. The calibration and object localization errors at the critical tool insertion task amounted to about 0.2 cm each, well within the allowed insertion error tolerance. This 0.2 cm error is referenced to the zoom-in view (fovy = 8 deg) from the overhead (front viw) camera which was bout 1 m away from the tool tip. For this zoom-in view, the average error on the image plane was typically 1.2 - 1.6% (3.2 -3,470 maximum error); a 1.4% average error is equivalent to a 0.2-cm displacement error on the plane 1 m in front of the camera,

The idea behind placing the high-fidelity graphics image over a real TV image is that the operator can interact with it visually in real time on a monitor within one perceptive frame when generating motion commands manually or by a computer algorithm. Thus, this method compensates in real time for the operator's visual absence from reality due to the time-delayed image. Typically, the geometric dimensions of a monitor and the geometric dimensions of the real work scene shown on the monitor are quite different. For instance, an 8-in. -long trajectory on a monitor can correspond to a 24-in. -long trajectory in the actual work space, that is, three times longer than the apparent trajectory on the monitor screen. Therefore, to preserve fidelity between a previewed graphics arm image and actual arm motions, all previewed actions on the monitor were scaled down very closely to the expected real motion rate of the arm hardware. The manually generated trajectories were also previewed before sending the motion commands to the GSFC control system to verify that all motion data were properly recorded. Preview displays contribute to operational safety. To eliminate the problem associated with the varying time delay in data transfer, the robot motion trajectory command is not executed at the GSFC control system until all the data blocks for the trajectory are received. An element of fidelity between the graphics arm image and actual arm motion was given by the requirement that the motion of the graphics image of the arm on the monitor screen be controlled by the same software that controls the motion of the actual arm hardware. This is required to implement the GSFC control software in the JPL graphics computer.

A few seconds after the motion commands were transmitted to GSFC from JPL, the JPL operator could view the motion of the real arm on the same screen where the graphics arm image motion was previewed. If everything went well, the image of the real arm followed the same trajectory on the screen that the previewed graphics arm image motion previously described, and the real arm image motion on the screen stopped at the same position where the graphics arm image motion stopped earlier. After completion of robot arm motion, the graphics images on the screen were updated with the actual final robot joint angle values. This update eliminates accumulation of motion execution errors from the graphics image of the robot arm, and retains the robot arm graphics image position fidelity on the screen even after the completion of a force sensor referenced compliance control action.

The actual contact events (moving the tool within the hole and moving the module out from or into the satellite's frame) were automatically controlled by an appropriate compliance control algorithm referenced to data from a force-moment sensor at the end of the robot arm, implemented by the cooperating GSFC team and invoked by the JPL operator when needed.

The experiments have been performed successfully, showing the practical utility of high-fidelity predictive-preview display techniques, combined with sensor-referenced automatic compliance control, for a demanding telerobotic servicing task under communication time delay. More on these experiments and on the related error analysis can be found in [15, 16]. Figures 14a and 14b illustrate a few typical overlay views.

A few notes arc in order here regarding the use of calibrated graphics overlays for time-delayed remote control.

1) There is a wealth of computation activities that the operator has to exercise. This requires very careful design considerations for an easy and user friendly operator interface to this computation activity.

2) The selection of the matching graphics and TV image points by the operator has an impact on the calibration results. First, the operator has to select significant points. this requires some rule-based knowledge about what is a significant point in a given view. Second, the operator has to use good visual acuity to click the selected significant points by the mouse.

Lessons Learned

The following general conclusions emerged so far from the development and experimental evaluation of the JPL Al'OP.:

1) The sensing, computer- and graphics-aided advanced teleoperation system truly provides ncw and improved technical features. To transform these features into new and improved task performance capabilities, the operators of the system have to be transformed from naive to skilled *operators.* This transformation is primarily an undertaking of education and training.

2) To carry out an actual task requires that the operator follow a clear procedure or protocol which has to be worked out off line, tested, modified, and finalized. It is this procedure or protocol following habit that finally will help develop the experience and skill of an operator.

3) The final skill of an operator can be tested and graded by the ability to successfully recover from unexpected errors and complete a task.

4) The variety of l/O activities in the ATOP control station requires workload distribution between two operators. The primary operator controls the sensing and computer-aided robot arm system, while the secondary operator controls the TV camera an monitor system and assures protocol following. Thus, the *coordinated training of two cooperating operators is* essential to successful use of the ATOP system for performing realistic tasks. It is not yet known what a single operator could do and how. To configure and integrate the current ATOP control station for successful use by a *single operator* is challenging research and development work.

5) The problem of ATOP system development is not only to find ways to improve technical components and to create new subsystems. The final challenge is to integrate the improved or new technical features with the natural capabilities of the operator through appropriate human-machine interface devices and techniques to produce an improved overall system performance capability in which *the operator is part of the system* in some new way.

III. ANTHROPOMORPHIC TELEMANIPULATION

The robot arms employed in the JPL ATOP project are of the industrial type with industrial type parallel claw end effecters. This sets definite limits for the arms' task performance capabilities as dexterity in manipulation resides in the mechanical and sensing capabilities of the hands (or end effectors). W c noted that, existing space manipulation tasks (except the handling of large space cargos) are designed for astronauts, including the tools used by astronauts. There are well over two hundred tools that are available today and certified for use by Extra Vehicular Activity (EVA) astronauts in space, Motivated by these facts, an effort parallel to the ATOP project was initiated at JPL to develop and evaluate human-equivalent or human-rated dexterous telemanipulation capabilities for potential applications in space because all manipulation related tools used by EVA astronauts are human rated.

The general technical approach adopted in this project implies the following: 1) the master arm is a replica of the slave arm, and each arm has seven DOF, 2) the master arm is solidly attached to the operator's arm, 3) forces acting on the slave arm can backdrive the master arm so that the operator can feel the forces/moments acting on the slave arm, 4) the slave hand is a human-like fingered hand with a replica glove-like master controlled attached solidly to the operator's hand, and 5) forces acting on the slave fingers can backdrive the fingers of the master glove so that the operator can feel the forces acting on the slave fingers. The ability of the operator to feel forces acting at the remote slave site provides kinesthetic telepresence to the operator. This enables the operator to perform sensitive, force-compliant manipulation tasks with or without tools.

The actual design and laboratory prototype development included the following specific technical features: 1) the system is fully electrically driven; 2) the hand and glove have four fingers (little finger is omitted) and each linger has four DOF; 3) the base of the slave fingers follow the curvature of the human fingers' base on the hand; 4) the slave hand and wrist forma mechanically integrated closed subsystem, that is, the hand cannot be used without its wrist; 5) the lower slave arm which connects to the wrist houses the full electromechanical drive system . . for the hand and wrist (altogether 19 DOF), including control electronics and microprocessors; and 6) the slave drive system electromechanically emulates the dual function of human muscles, namely, position and force control. This implies a novel and unique implementation of active compliance. All of the specific technical features taken together make this exoskeleton unique among the few similar systems, No other previous or ongoing developments have all the aforementioned technical features in one integrated system, and some of the specific technical features arc not represented in any other similar systems at all, More on this system can be found in [24].

Currently, the JPL anthropomorphic telemanipulation system is assembled and tested in a terminus control configuration. In this configuration the master glove is integrated with our previously developed nonanthropomorphic six-DOF force-reflecting hand controller (FRHC), and the mechanical hand and forearm are mounted to an industrial robot (PUMA 560), replacing its standard forearm. The notion of terminus control mode refers to the fact that only the terminus devices (glove and robot hand) are of anthropomorphic nature, and the master and slave arms are nonanthropomorphic. The system is controlled by a high-performance distributed computer controller. Control electronics and computing architecture. were custom developed for this telemanipulation system.

The present control electronics architecture for the master glove and the anthropomorphic hand/wrist is shown in Fig. 15. It is comprised of PC-based computational engines, using TMS320C40 (C40) processors and two custom designed intelligent controllers. The interface to the FRHC and the PUMA upper arm joints is provided by two separate universal motor controllers (UMC). The UMC has been described previously in [8]. The C40S communicate with each other via a single duplex communication channel. The intelligent controllers are based on the Texas Instrument TMS320C30 (C30). The C30 was selected for this task because of its low cost and high performance (33 MFLOPS). The C30 is very similar to the C40 except that it lacks the six high-speed communication ports. The two intelligent controllers are placed near the system's sensors, one is near the master glove, the other is near the anthropomorphic hand and wrist. The function of the controllers is to provide a sampling of analog signals, filter these signals, provide digital calibration of strain gages, model the actuator voltage-velocity curve, generate pulse-width modulated (PWM) signals, and communicate with the PC-based computational engine. All programs are written in the C language, using the SPOX Real-Time Operating System (Spectrum Microsystems) to facilitate the development of multipurpose programs. More on this system can be found in [25].

The anthropomorphic telemanipulation system in terminus control configuration is shown in Fig. 16. The master arm/glove and the slave arm/hand have 22 active joints each. The manipulator lower arm has five additional drives to control finger and wrist compliance. This active electromechanical compliance (AEC) system provides the muscle equivalent dual function of position as well as stiffness control. A cable links the forearm to an overhead gravity balance suspension system, relieving the PUMA upper arm of this additional weight. The forearm has two sections, one rectangular and one cylindrical. The cylindrical section, extending, beyond the elbow joint, contains the wrist actuation system. The rectangular cross section houses the linger drive actuators, all sensors, and the local control and computational electronics. The wrist has three DOF with natural displacements similar to the human wrist, The wrist is linked to an AEC system that controls the wrist's stiffness, It is noted again that the slave hand, wrist, and forearm form a mechanically closed system, that is, the hand cannot be used without its wrist. A glove-type device is worn by the operator. Its force sensors enable hybrid position/force control and compliance control of the mechanical hand. Four fingers are instrumented, each having four DOF. Position feedback from the mechanical hand provides position control for each of the 16 glove joints. The glove's feedback actuators are remotely located and linked to the glove through flex cables. One-to-one kinematic mapping exists between the master glove and slave hand joints, thus reducing the computational efforts and control complexity of the terminus subsystem. The exceptions to the direct mapping are the two thumb base joints which need kinematic transformations.

The system is currently being evaluated, focusing on tool handling and astronaut equivalent task executions. The evaluation revealed the system's potential for tool handling but it also became evident that EVA tool handling operations in space require a dexterous, human-equivalent *dual* arm robot.

IV. NEW DEVELOPMENT TRENDS

Applications of teleoperators or telerobots are numerous, in particular in the nuclear and munitions industries, maintenance and reclaiming industries operating, in hostile environments, and in industries that support space and underwater operations and explorations. Lately, robotics and teleoperation technology started breaking ground also in the *medical field*. Diagnostic and actual operative surgeries, including microsurgery and telesurgery within the general frame of *telemedicine*, *seem* to be receptive fields for potential use of robotic and teleoperator tools and techniques. More details on this new medical application trend can be found in [26, 27].

The application of robotic and teleoperator tools and techniques in the field of medicine is quite real. To demonstrate this, a surgeon in Milan, Italy very recently (in August, 1995) performed a live prostate telebiopsy on a real patient located at about 25 km distance from the surgeon. This was shown to about 350 attendees of a technical Congress in real time. The real technical point in this act was the application of telerobotic measurement and tool handling techniques. First, an automated calibration system determines the coordinates of a visually identified point of interest in an echographic image of a prostate, then, upon command from the surgeon, the robot arm inserts the biopsy tool to that point with high precision. (See the technical details in [28, 29].) The claim, announced by the surgeon, was that this "telerobotic procedure" can provide better accuracy and can be performed in shorter time than a purely manual procedure. An additional technical point in this claim was that a low-cost PC-based telecommunication system in a limited bandwidth ISDN network setting can provide a satisfactory system capability for this type of "telerobotic procedure" in telemedicine.

Acknowledgment

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] Sheridan, T. B., *Telerobotics, Automation, and Human Supervisory Control,* The MIT Press, Cambridge, MA, London, England, 1992,

[2] Bejczy, A. K., and Salisbury, J. K., "Controlling Remote Manipulators Through Kinesthetic Coupling," *Computers in Mechanical Engineering,* Vol. l, No. 1, 1983; also, "Kinesthetic Coupling Between Operator and Remote Manipulator," *Proceedings of the ASME international Computer Technology Conference Vol. 1* (San Francisco, CA), ASME, New York, 1980, pp. 192-211.

[3] Bejczy, A. K., "Teleoperation: The Language of the Human Hand," *Proceedings of the IEEE Workshop on Robot and Human Communication,* Tokyo, Japan, Sept. 1-3, 1992,

[4] Bejczy, A. K., Szakaly, Z., and Kim, W, S., "A Laboratory Breadboard System for Dual Arm Teleoperation," *Third Annual Workshop on Space Operations, Automation and Robotics,* NASA Conf. Pub, 3059, Johnson Space Center, Houston, TX, July 1989, pp. 649-660.

[5] Bejczy, A. K., and Szakaly, Z., "Performance Capabilities of a JPL Dual-Arm Advanced Teleoperation System," *Space Operations, Applications, and Research Symposium (SOAR '90) Proceedings,* Albuquerque, NM, June 26, 1990, pp. 168-179.

[6] Bejczy, A. K., Szakaly, Z., and Ohm, T., "Impact of End Effecter Technology on Telemanipulation Performance," *Third Annual Workshop on Space Operations, Automation and Robotics,* NASA Conf. Pub. 3059, Johnson Space Center, Houston, TX, 1989, pp. 429-440,

[7] Bejczy, A. K., and Szakaly, Z., "An 8-D.O.F. Dual Arm System for Advanced Teleoperation Performance Experiments," *Space Operations, Applications, and Research Symposium (SOAR '91), NASA No. 3127,* Houston, TX, 1991, pp. 282-293; also Lee, S., and Bejczy, A. K., "Redundant Arm Kinematic Control Based on Parametrization,"

Proceedings of the IEEE International Conference on Robotics and Automation, Sacramento, CA, April 1991, pp. 458-465.

[8] Bejczy, A. K., and Szakaly, Z. F., "Universal Computer Control System (UCCS) for Space Telerobots," *Proceedings of the IEEE Int'l Conference on Robotics and Automation,* Raleigh, NC, March 30-April 3, 1987.

[9] Bejczy, A. K., and Szakaly, Z., "A Harmonic Motion Generator for Telerobotic Applications," *Proceedings of IEEE lnt'1 Conference on Robotics and Automation* (Sacramento, CA), 1991, pp. 2032-2039.

[10] Bejczy, A. K., Kim, W. S., and Venema, S., "The Phantom Robot: Predictive Display for Teleoperation with Time Delay," *Proceedings of IEEE International Conference on Robotics and Automation*, Cincinnati, OH, May 1990, pp. 546-550.

[11] Bejczy, A. K., and Kim, W. S., "Predictive Displays and Shared Compliance Control for Time Delayed Telemanipulation," *Proceedings of IEEE International Workshop on Intelligent Robots and Systems* (IROS '90), Tsuchiura, Japan, July 1990 pp. 407-412.

[12] Kim, W. S., and Bejczy, A. K., "Graphics Displays for Operator Aid in Telemanipulation," *Proceedings of IEEE International Conference on Systems, Man and Cybernetics,* Charlottesville, VA, Oct. 1991, pp. 1059-1067.

[13] Kim, W. S., "Graphical Operator interface for Space Telerobotics," *Proceedings of IEEE International Conference on Robotics and Automation,* Atlanta, GA, May 1993, p. 95.

[14] Fiorini, P., Bejczy, A. K., and Schenker, P., "Integrated Interface for Advanced Teleoperation," *IEEE Control Systems Magazine,* Vol. 13, No. 5, Oct. 1993, pp. 15-20.

[15] Kim, W. S., and Bejczy, A. K., "Demonstration of a High-Fidelity Predictive/Preview Display Technique for Telerobotics Servicing in Space," *IEEE Transactions on Robotics and Automation, Oct. 1993, Special Issue on Space Telerobotics*, pp. 698-702; also Kim, W. S., Schenker, P. S., Bejczy, A. K., Leake, S., and Ollendorf, S., "An Advanced Operator Interface Design with Preview/Predictive Displays for Ground-Controlled Space

Telerobotic Servicing," *SPIE Conference* No. *2057: Telemanipulator Technology and Space Telerobotics*, Boston, MA, Sept. 1993.

[16] Kim, W. S., "Virtual Reality Calibration for Telerobotic Servicing," *Proceedings of the IEEE International Conference on Robotics and Automation, San Diego,* CA, May 1994, pp. 2769=2775.

[17] Lee, P., Hannaford, B., and Wood, L., "Telerobotic Configuration Editor," *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, Los Angeles, CA 1990, pp. 121-126

[18] Hannaford, B., Wood, L., Guggisberg, B., McAffee, D., and Zak, H., "Performance Evaluation of a Six-Axis Generalized Force-Reflecting Teleoperator," *Jet Propulsion Lab., JPL Pub. 89-18,* Pasadena, CA, June 15, 1989.

[19] Hannaford, B., Wood, L., Guggisberg, B., McAffee, D., and Zak, H., "Performance Evaluation of a Six-Axis Force-Reflecting Teleoperation," *IEEE Transaction on Systems, Man and Cybernetics,* Vol. 21, No. 3, 1991.

[20] Das, H., Zak, H., Kim, W. S., Bejczy, A. K., and Schenker, P. S., "Performance Experiments with Alternative Advanced Teleoperator Control Modes for a Simulated Solar Max Satellite Repair," *Proceedings of Space Operations, Automation and Robotics Symposium (SOAR '91) NASA No. 3127*, Johnson Space Center, Houston, TX, July 9-11, 1991, pp. 294-301.

[21] Das, H., Zak, H., Kim, W. S., Bejczy, A. K., and Schenker, P. S., "Performance with Alternative Control Modes in Teleoperation," *PRESENCE: Teleoperators and Virtual Environments*, MIT Press Pub., Massachusetts Inst. of Technology, Cambridge, MA, Vol. 1, No. 2, 1993, pp. 219-228.

[22] Fiorini, P., Giancaspro, A., Losito, S., and Pasquariello, G., "Neural Networks for Segmentation of Teleoperation Tasks," *PRESENCE: Teleoperators and Virtual*

Environments, MIT Press Pub., Massachusetts Inst. of Technology, Cambridge, MA, Vol. 2, No. 1, 1993, pp. 66-81.

[23] Hannaford, B., and Lee, P., "Hidden Markov Model Analysis of Force-Torque information in Telemanipulation," *international Journal of Robotics Research*, Vol. 10, No. 5, 1991.

[24 Jau, B. M., "Man-Equivalent Teleopresence Through Four Fingered Human-Like Hand System," *Proceedings of the IEEE International Conference on Robotics and Automation* (Nice, France), IEEE Press, Los Alamitos, CA, 1992, pp. 843-848.

[25] Jau, B. M., Lewis, M. A., and Bejczy, A. K., "Anthropomorphic Telemanipulation System in Terminus Control Mode," *Proceedings of ROMANSY '94* (Gdansk, Poland), 1994, Springer-Verlag, Berlin, Germany.

[26] *Proceedings of the First Int '1 Symp. on Medical Robotics and Computer Assisted Surgery,* Shadyside Hospital, Pittsburgh, PA, Sept. 22-24, 1994.

[27] *interactive Technology and the New Paradigm foı Healthcare; Medicine Meets Virtual Reality Proceedings, 10S* Press, Amsterdam, Oxford, Washington DC, OHMSA, Tokyo, Osaka, Kyoto, 1995.

[28] Rovetta, A. and Sal a, R., Execution of Robot-Assi steal Biopsies within the Clinical Context, *Proceedings of the 9th World Congress on the Theory of Machines and Mechanisms,* Milan, Italy, August 29-Sept. 2, 1995.

[29] Sala, R., Construction of a New Automatic Telemeter for Medical Applications and Robotic Telesurgery, *Proceedings of the 9th World Congress on the Theory of Machines and Mechanisms,* Milan, Italy, August 29-Sept. 2, 1995.

Some Related Bibliography

Backes, P. G., "Ground-Remote Control for Space Station Telerobotics with Time Delay," *Proceedings of the AAS Guidance and Control Conference*, A AS Paper No. 92-052, Keystone, CO, Feb. 8-12, 1992.

Backes, P. G., "Supervised Autonomous Control, Shared Control, and Teleoperation for Space Servicing," *Proceedings Space Operations, Applications, and Research Symposium,* Houston, TX, Aug. 4-6, 1992.

Baron, S. and Kleinmann, D. C., The Human as an Optimal Controller and Information Processor, *IEEE Transactions on Man-Machine Systems,* MMS-1O, 1, 1969, pp. 9-17.

Bejczy, A., Kinesthetic and Graphic Feedback for Integrated operator Control, *Proceedings of the Sixth Annual Advanced Control Conference,* April 28-30, 1980, Purdue University, West Lafayette, Indiana, pp. 137-147.

Bejczy, A., Sensors, Controls, and Man-Machine Interface for Advanced Teleoperation, *Science, 208, 1980,* pp. *1327-1335.*

Bejczy, A. K., Brooks, T. L., and Mathur, F. P., *Servomanipulator Man-Machine Interface Conceptual Design,* JPL Report No. 5030-507, U.S. Dept. of Energy, August 1981.

Brooks, T., Superman: A System for Supervisory Manipulation and the Study of Human-Computer Interactions, *Master's Thesis,* Man-Machine Systems Laboratory, Massachusetts Institute of Technology, May 1979.

Ferrell, W. R. and Sheridan, T. B., Supervisory Control of Remote Manipulation, *IEEE Spectrum,* October)967, 4,81-88.

Ferrell, W. R., Command Language for Supervisory Control of Remote Manipulation, in E. Hccr (Ed.), *Remotely Manned Systems,* California Institute of Technology, Pasadena, California, 1973, pp. 369-373.

Funds, J., Lindsay, T. S., and Paul, R. P., "Teleprogramming: Toward Delay-Invariant Remote Manipulation," *Presence*, Vol. l, No. 1, 1992, pp. 29-44.

Groome, R. C., Force Feedback Steering of Teleoperator System, MS *Thesis*, Massachusetts Institute of '1'ethnology, Department of Aeronautics and Astronautics, 'Cambridge, Massachusetts, August 1977.

Handlykken, M., and Turner, T., Control Systems Analysis and Synthesis for a Six Degree-of-Freedom Universal Force-Reflecting Hand Controller, *Proceedings of the Nineteenth IEEE Conference on Decision and Control*, December 10-12, 1980, Albuquerque, New Mexico, pp. 1197-1205.

Hayati, S., and Venkataraman, S. T., "Design and Implementation of a Robot Control System with Traded and Shared Control Capability," *Proceedings of the IEEE International Conference on Robotics and Automation,* 1989, pp. 1310-1315.

Hill, J. W., and Sword, A., Manipulators Based on Sensor Directed Control: An Integrated End Effecter and Touch Sensing System, *Proceedings of the Seventeenth Annual Conference in Human Factors*, October 1979, Washington, D.C.

Hill, J. W., Study of Modeling and Evaluation of Remote Manipulation Tasks with Force Feedback, *Final Report For JPL, SRI Project 7696 JPL Contract 9.5-5170*, March 1979.

Jagacinski, R. J., and Miller, R. A., Describing the Human Operator's Internal Model of a Dynamic System, *Human Factors, 20 (4), 1978,* pp. 425-433.

Jelatis, D. C., Characteristics and Evaluation of Master-Slave Manipulators, *Performance Evaluation of Programmable Robots and Manipulators, NBS Special Publication 459,* October 1975, pp. 141-145.

Johnson, E. G., and Corliss, W. R., *Human Factors Applications in Teleoperator Design and Operation,* John Wiley & Sons, Inc., 1971.

Kohler, G. W., *Manipulator Type Book,* Verlag Karl Thiemig, Munchen, FRG, 1981.

Nevins, J. L., Sheridan, T. B., Whitney, D. E., and Woodin, A. E., The Multi-Model Remote Manipulator System, in E. Heer (Ed.), *Remotely Manned Systems*, California institute of Technology, Pasadena, California, 1973, pp. 173-187.

Setzer, W. and Vossius, G., On the Stability Problem of Human Arm and Hand Movements Controlling External Load Systems, *Proceedings of the First Annual European Conference on Manual Control*, May 25-27, 1981, Delft University of Technology, Delft, The Netherlands, pp. 243-253.

Sheridan, T. B., Supervisory Control of Remote Manipulators, Vehicles and Dynamic Processes: Experiments in Command and Display Aiding, *M.I. T. Man-Machine Systems Laboratory Report*, Cambridge, Massachusetts, March 1983.

Shultz, R. E., Tesar, D., and Doty, K. L., Computer Augmented M anual Control of Remote Manipulator, *Proceedings of the 1978 IEEE Conference on Decision and Control,* San Diego, California, January 1979.

Spiger, R. J., Farrell, R. J., and Tonkin, M. H., Survey of Multi-Function Display and Control Technology, *NASA Report No. CR-I6751O,* Boeing, Co., 1982.

Stark, L. and Ellis, S. S., Revisited: Cognitive Models in Direct Active Looking, in *Eye Movement, Cognition and Visual Perception,* Fisher, Monty, and Senders (Eds.), Album Press, New Jersey, 1981, pp. 193-226.

Starr, G. P., Supervisory Control of Remote Manipulation: A Preliminary Evaluation, *Proceedings of the Seventeenth Annual Conference on Manual Control,* June 16-18, 1981, University of California, Los Angeles, California, pp. 95-107.

Starr, G. P., A Comparison of Control Modes for Time-Delayed Remote Manipulation, *IEEE Transactions on Systems, Man, and Cybernetics,* SMC-9 (4), 1979, pp. 241-246.

Stassen, H. G., Man as Controller, *introduction to Human Engineering,* Koln: Verlag TUV, Rheinland, 1976.

Vertut, J., Experience and Remarks on Manipulator Evaluation, Performance Evaluation *of Programmable Robots and Manipulators,* NBS Special Publication 459, October 1975, pp. 97-112.

Vertut, J., and Coiffet, P., *Teleoperations*, Vol. 3 in Robot Technology Series, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1983.

Vykukal, H. C., King, R. F., and Vallotton, W. C., An Anthropomorphic Master-Slave Manipulator System, in E. Heer (Ed.), *Remotely Manned Systems*, California Institute of Technology, Pasadena, California, 1973, pp. 199-205.

Wagner, E. and Hanett, A., MINI MAC - the Remote-Controlled Manipulator with Stereo TV Viewing at the SIN Accelerator Facility, *Transactions of the American Nuclear Society,* Vol. 30, pp. 759-760, 1978.

White, T. N., Modeling the Human Operator's Supervisory Behavior, *Proceedings of the First European Annual Conference on Human Decision Making and Manual Control,* May 25-27, 1981, Delft University of Technology, Delft, The Netherlands, pp. 203-217.

Yoerger, D. R., Supervisory Control of Underwater Telemanipulators: Design and Experiment, M. I. T., *Man-Machine Systems, Laboratory Report,* Cambridge, Massachusetts, August 1982.

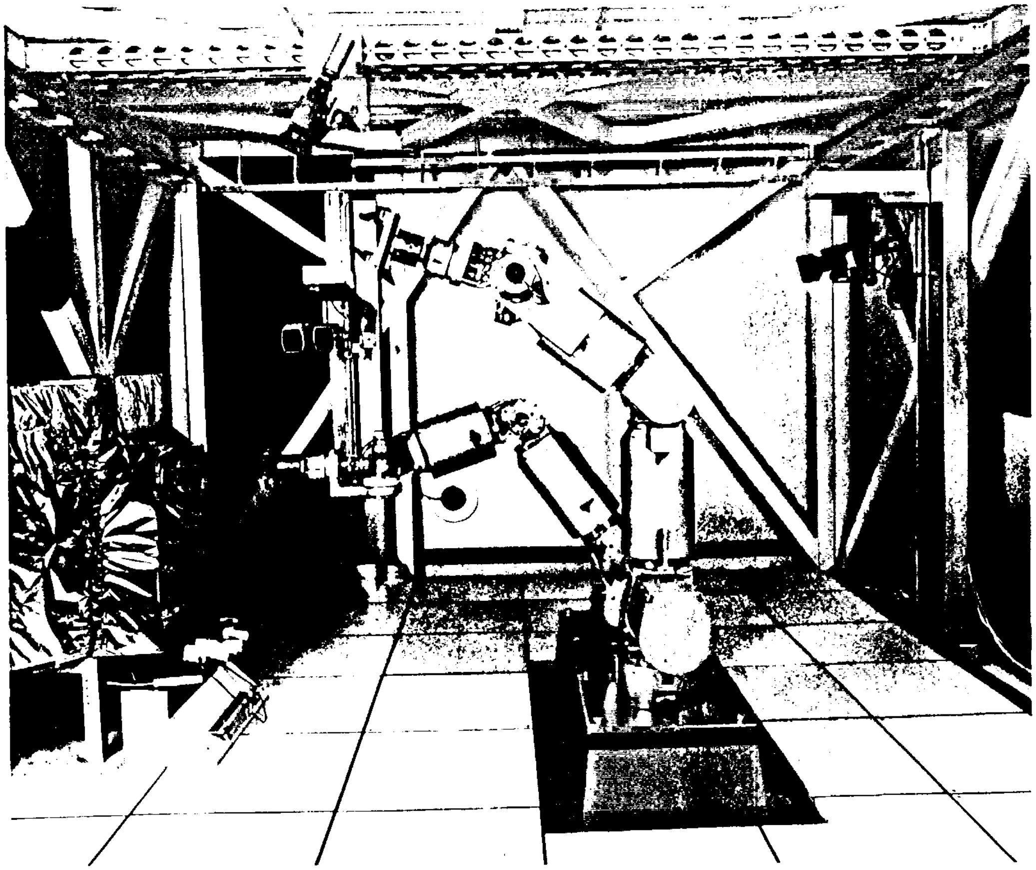

FIG. 1 JPL ATOP dual arm workcell with Gantry TV frame.

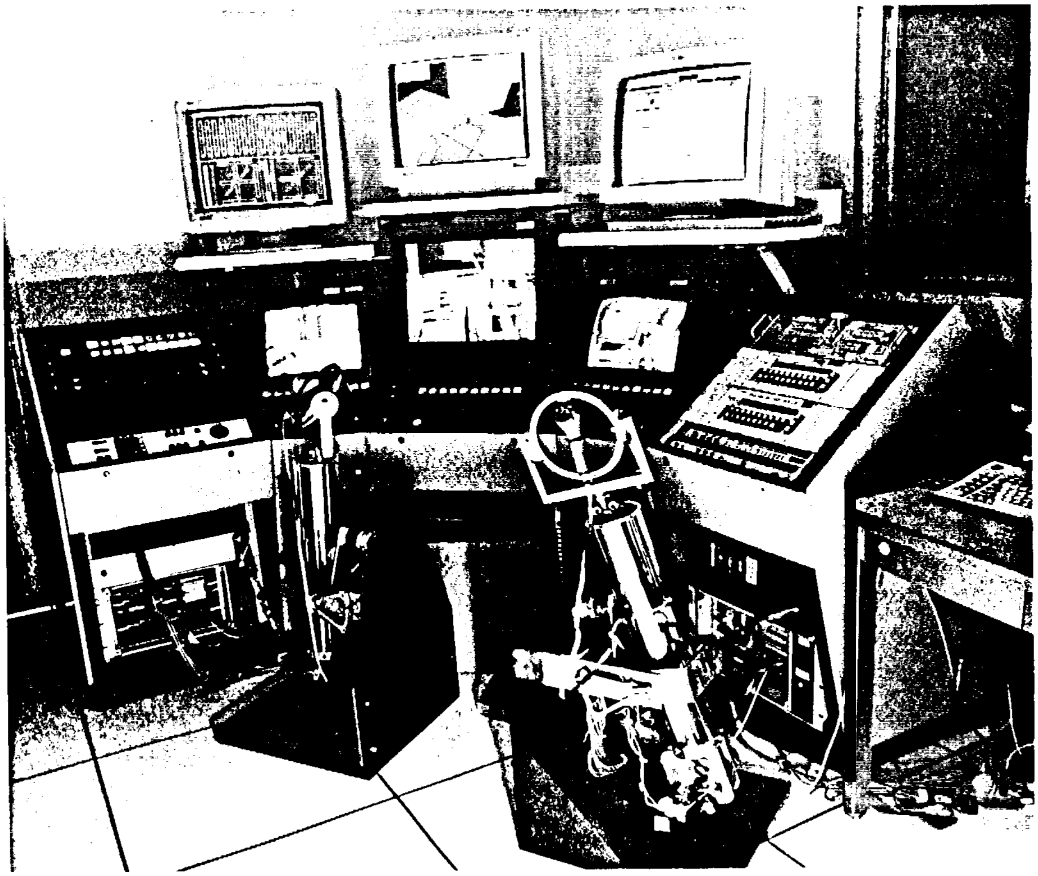

FIG. 2 **JPL ATOP control station.**

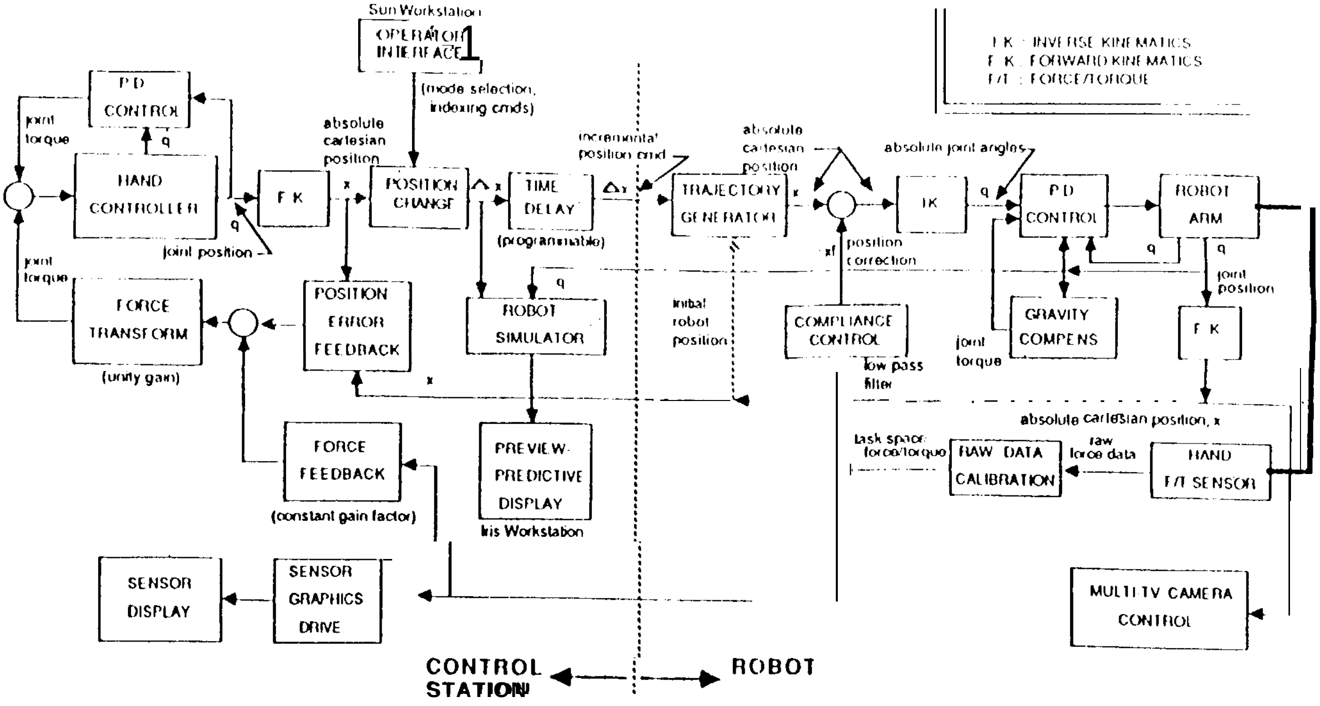

FIG. 3 Control system flow diagram,

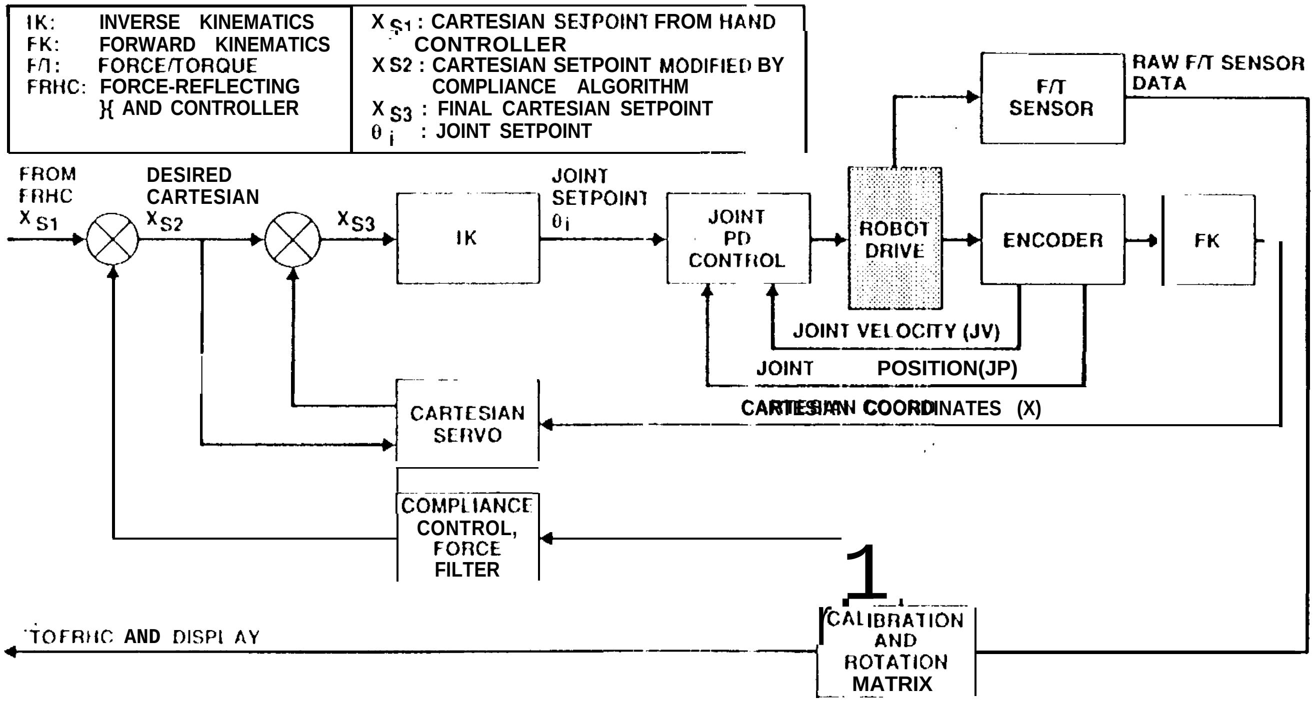

FIG. 4 Control schemes: joint servo, Cartesian servo, compliance control.

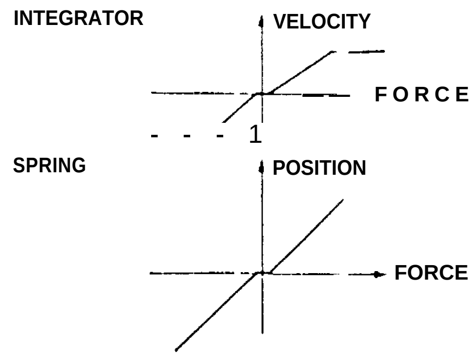

FIG. *5* **Compliance components and interpretations.**

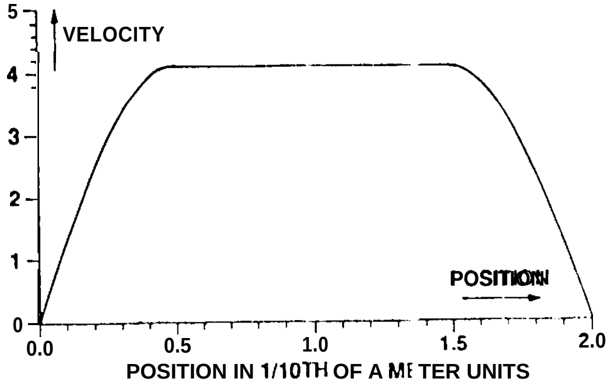

FIG. 6 Harmonic motion generator velocity-position function.

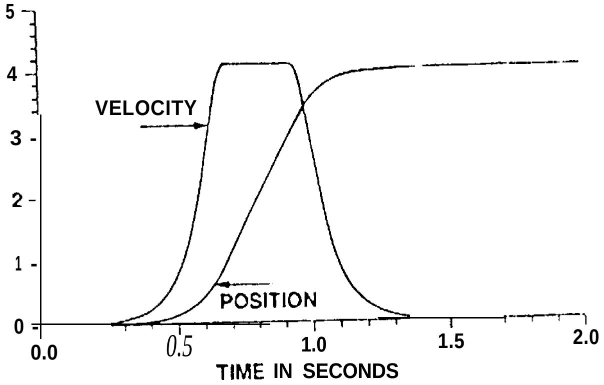

FIG. 7 Harmonic motion generator position and velocity time functions.

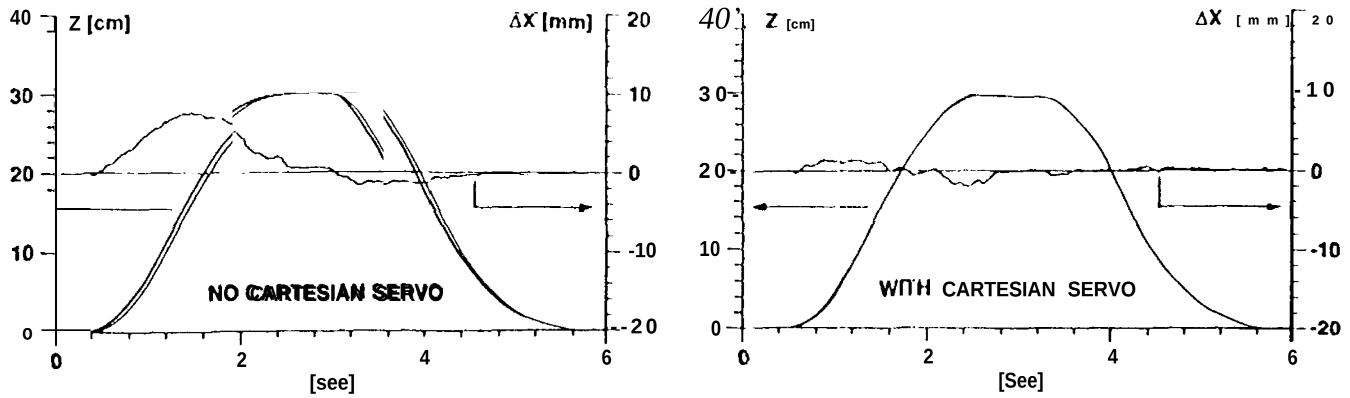

FIG. 8 **Vertical (Z) straight line trajectory from manual control and AX error.**

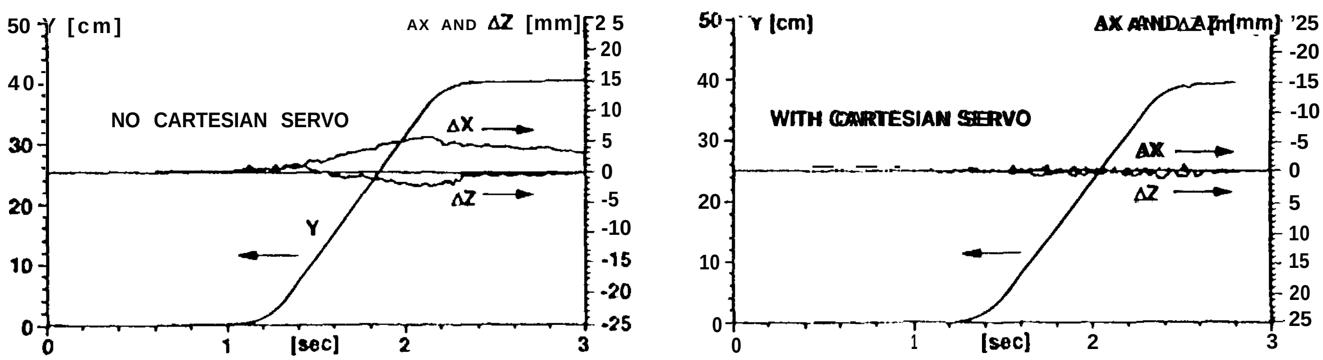

FIG. *9* **Horizontal (Y) straight line trajectory from harmonic motion generator and** AX **and** AY **errors.**

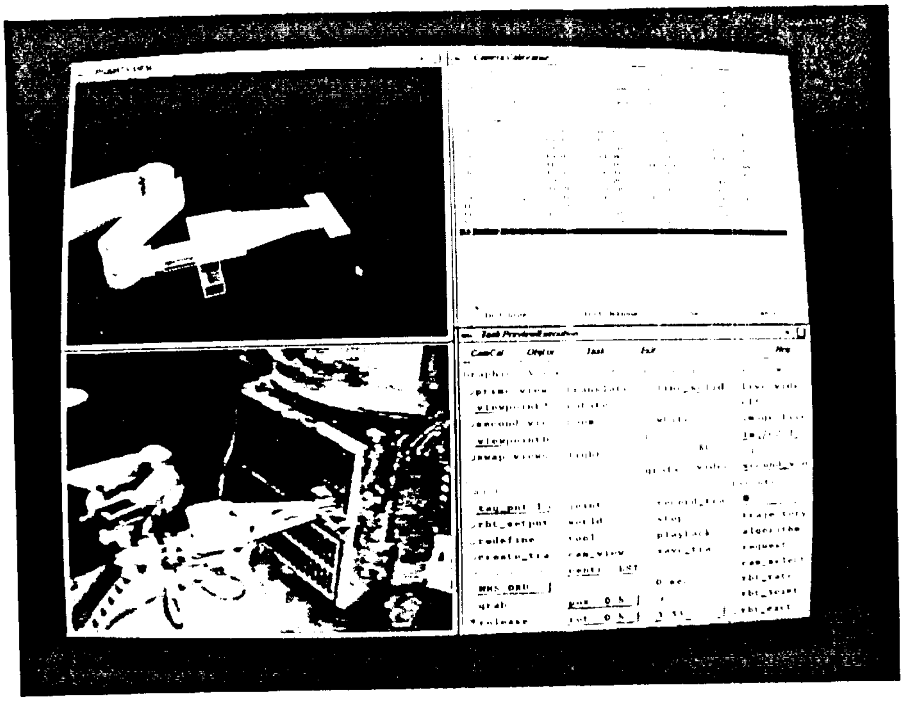

FIG. 10 Graphics user interface for calibrating virtual (graphics) images to TV images.

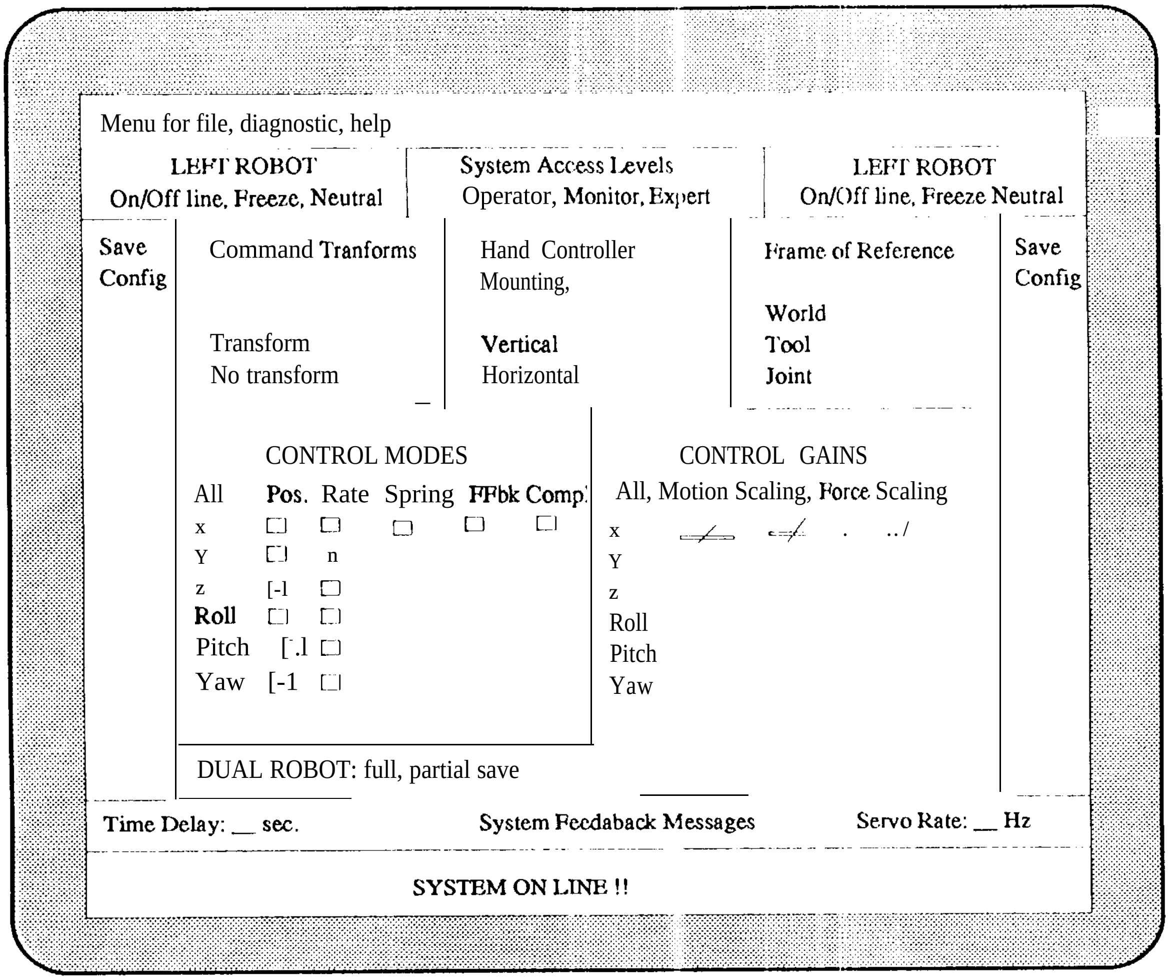

FIG. 11 **Schematic layout of the TCE interface.**

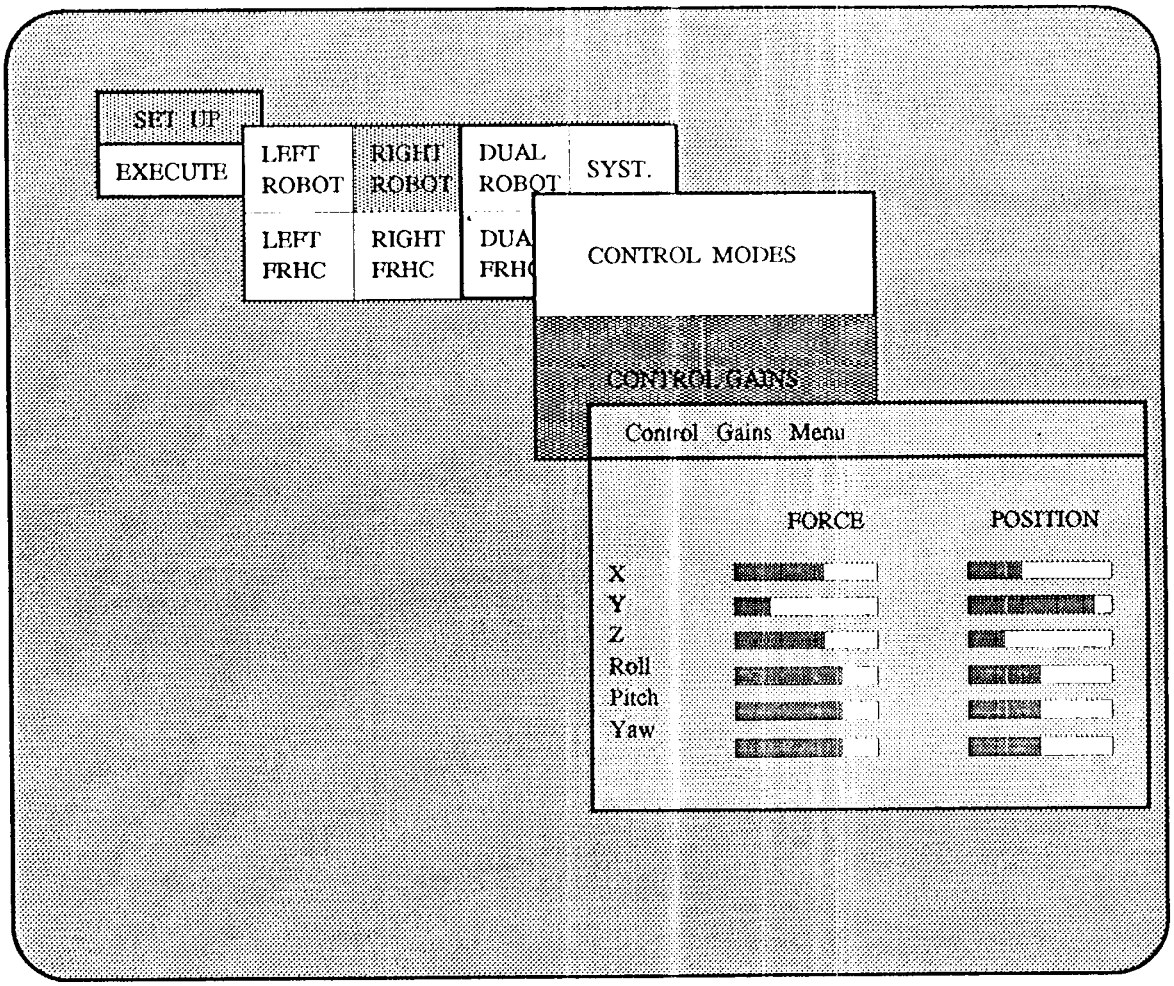

FIG. 12 **Schematic layout of the hierarchical data interface.**

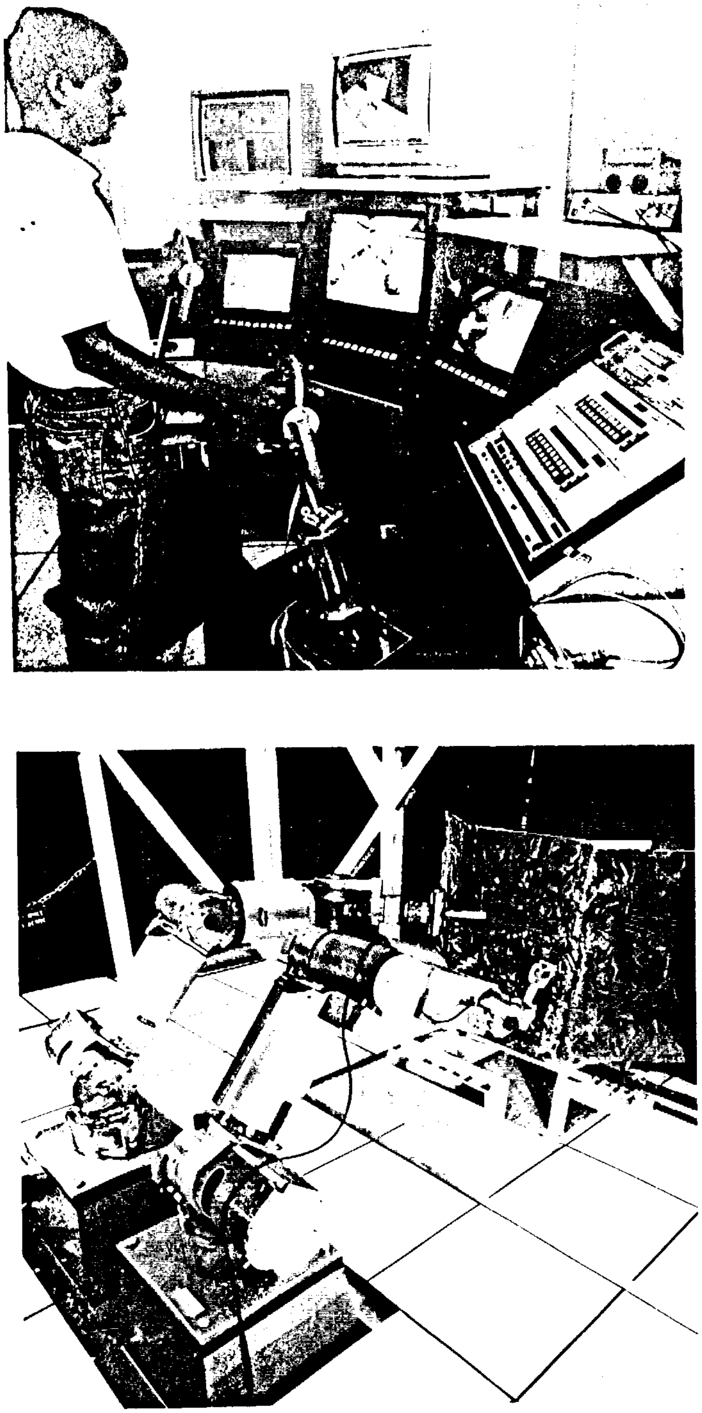

FIG. 13 SMSR repair subtask simulation, reinstating the satellite's thermal blanket.

Note: The two photos together as shown above form one figure!

Note: These two photos should be placed side-by-side!

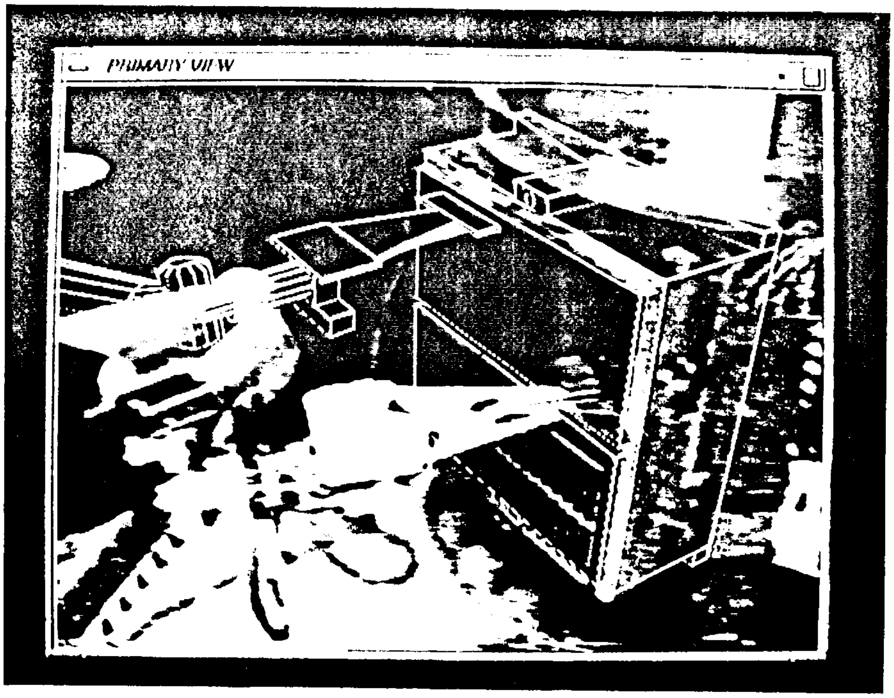

FIG. 14a **Predictive/pretiew display of end point motion.**

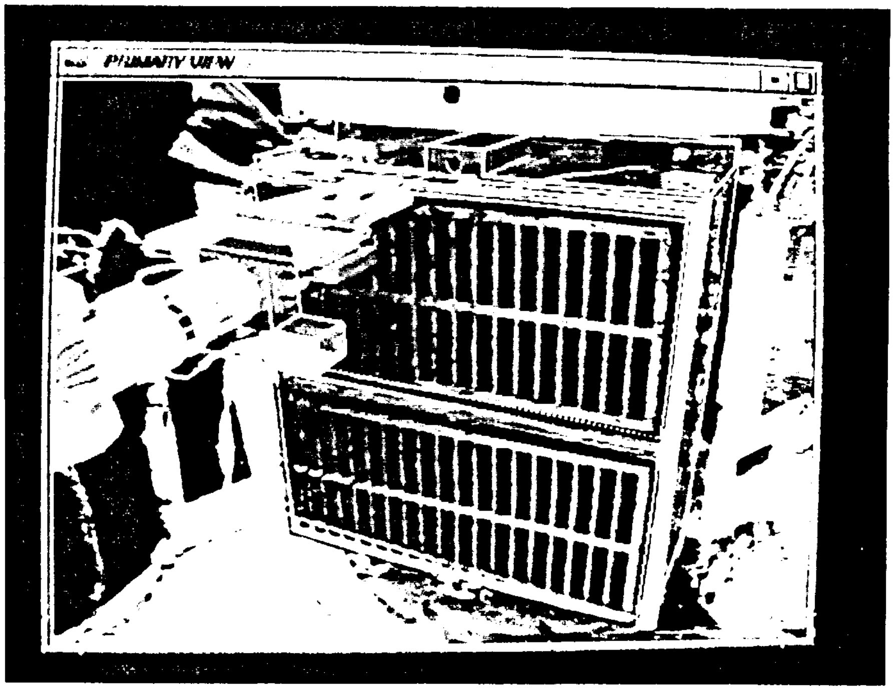

FIG. 14b **Status of predicted end point after motion execution, from a different camera view for the same motion shown in FIG. 14a.**

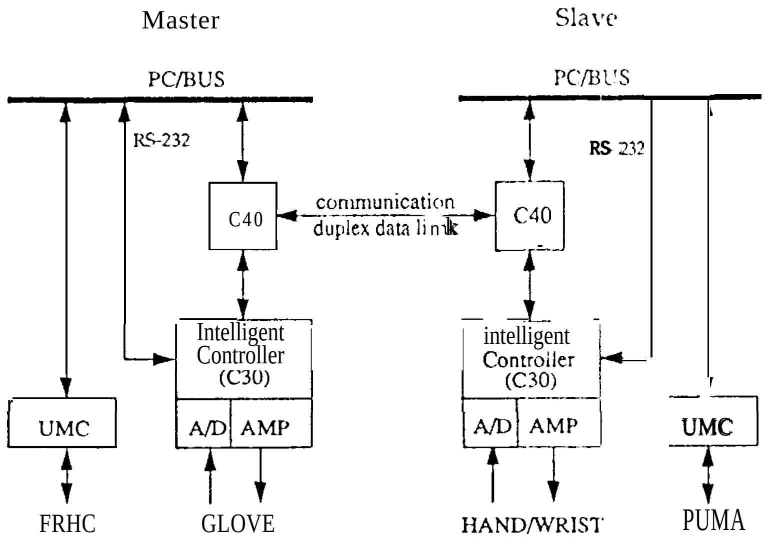

FIG. 15 **Control architecture overview.**

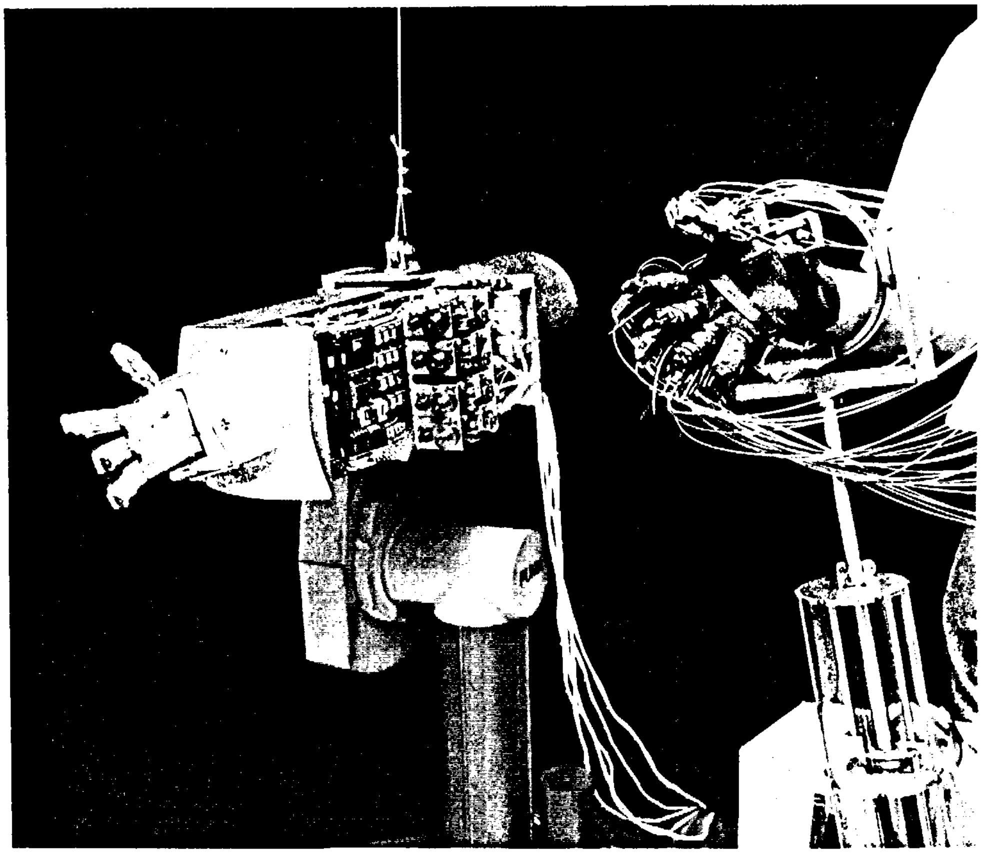

FIG. 16 **Master glove controller and anthropomorphic hand.**